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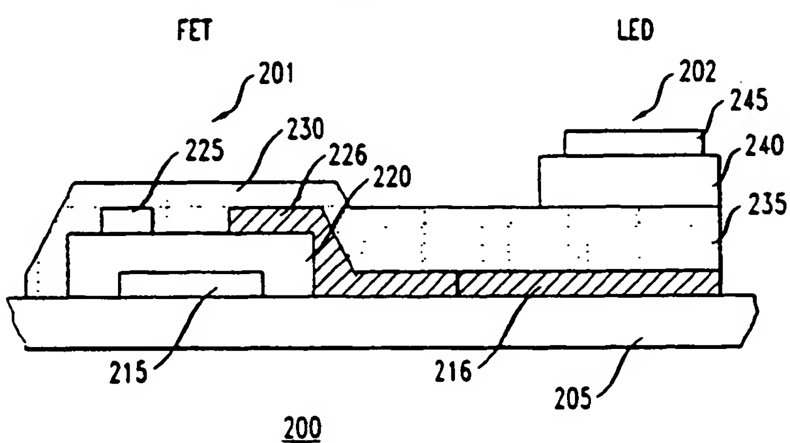
(54) Thin-film transistor monolithically integrated with an organic light-emitting diode

(57) A device in which one or more thin film transistors are monolithically integrated with a light emitting diode is disclosed. The thin film transistor has an organic semiconductor layer. The light emitting layer of the light emitting diode is also an organic material. The device is fabricated economically by integrating the fabrication of the thin film transistor and the light emitting diode on the substrate and by employing low cost fabrication techniques.

FIG. 2



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vices that are both economical and efficient.

[0011] If the device configuration is such that light is emitted from the LED through the substrate, the substrate must be transparent. Either glass substrates or transparent plastic substrates are contemplated as suitable. It is advantageous if the substrate is a transparent plastic substrate such as a polyester or polyimide substrate, because such substrates are inexpensive, durable, flexible, and lightweight. If the device configuration is such that the LED does not emit light through the substrate, opaque substrates such as silicon, steel, or opaque plastic substrates are contemplated as suitable.

[0012] In the embodiments of the present invention wherein the light emission is through the substrate, the anode of the LED device formed directly on the transparent substrate is also transparent. Examples of suitable transparent anode materials are transparent conducting metal oxides such as indium tin oxide (ITO).

[0013] The gate contact of the organic TFT is also formed directly on the transparent substrate. Again suitable materials for the gate contact of a TFT with an active organic layer are well known to one skilled in the art. Examples of suitable materials include vacuum evaporated metals such as gold, aluminum, and platinum. Soluble conducting polymers such as polyaniline, poly(3,4-(ethylene-dioxy)thiophene) and polypyrrole are also contemplated as suitable. Conductive particle-based polymer composites such as silver ink and graphite ink are also contemplated as suitable.

[0014] In the device configuration wherein the transparent anode of the LED is formed directly on the transparent substrate, it is advantageous if the gate contact of the organic TFT and the anode of the organic LED are the same material so that both can be formed using one deposition step and one lithographic processing sequence. Consequently, in the embodiments of the present invention wherein the LED anode is a transparent metal oxide, it is advantageous if the gate contact is the same transparent metal oxide.

[0015] A layer of insulating material is formed over the gate contact. Insulating materials suitable for use in organic TFT devices are well known and all are contemplated as suitable. Examples of suitable materials are inorganic material such as silicon oxide (SiO_2) and silicon nitride (Si_3N_4). Soluble polymer dielectrics such as polyimide and poly(methyl methacrylate) are also contemplated as suitable. Other examples of suitable dielectric materials include photodefinable polymer dielectrics such as benzocyclobutene and commercially available spin-on glass materials. From a processing perspective, it is advantageous if the insulating layer is either a soluble polymer dielectric material, a photodefinable dielectric material or a spin-on glass. Such materials are advantageous because layers of these materials are formed on the substrate by low-cost processing techniques such as spin-coating, casting and printing (e.g. screen printing, ink-jet printing, soft lithography patterning and spraying). Soft lithography is described in Qin, D., et al., "Microfabrication, Microstructures and Microsystems," Topics in Current Chemistry, Vol 194 p. 2-20 (1998), which is hereby incorporated by reference.

[0016] The organic TFT device has source and drain contacts. Materials suitable for use as the source and drain contacts for the organic TFT device are well known and all are contemplated as suitable. Examples of suitable materials include the above-described vacuum evaporated metals, soluble conducting polymers, and conductive particle-based polymer composites. Typically the source and drain contacts are formed over the insulating layer or over a layer of organic semiconductor material formed over the insulating layer.

[0017] Examples of suitable organic semiconductor materials with suitable field effect mobilities and other desirable semiconductor properties are well known to one skilled in the art. Such materials are either p-type materials or n-type materials. A variety of techniques are employed for depositing a layer of such materials. For example, layers of p-type conjugated oligomers such as thiophene oligomers, oligomers with fused ring moieties, and metallophthalocyanines are formed by vacuum evaporation. Layers of n-type materials such as fluorinated metallophthalocyanines, anhydrides such as perylenetetracarboxylic dianhydride and imide derivatives thereof, C_{60} and tetracyanonaptho-2,6-quinodimethane are contemplated as suitable. Other examples of suitable organic semiconductor materials are soluble conjugated polymers, oligomers, and fused ring molecules. Soluble semiconductor materials are advantageous because layers of these materials are formed using low-cost processing techniques such as screen-printing, ink-jet printing, soft lithography patterning, and spray applications.

[0018] Over the anode of the LED is formed an organic hole transporter layer. Organic hole transporter layers are well known to one skilled in the art. The p-type organic semiconductor materials described above are also suitable for use as the hole transporter layer for the LED. It is advantageous if the material for the hole transporter layer is the same as the material for the semiconductor material to limit the number of deposition and patterning steps required to fabricate the device.

[0019] An electron transport/light emitter layer is formed over the organic hole transporter layer. In one embodiment of the present invention, the electron transport layer is 8-hydroxyquinolinato aluminum (Alq). A cathode is then formed over the electron transport layer.

[0020] The above-described device is advantageous not only because of its performance, but because it can be manufactured economically both from a cost of materials perspective and a cost of processing perspective. In this regard, it is advantageous if a device configuration is selected that permits simultaneous deposition of layers for both devices (e.g. the anode of the LED and the gate of the TFT; the semiconductor layer for the TFT and the hole transporter layer of the LED). In this regard,

approaches, the dielectric layer is formed on the patterned conducting layer using printing methods. For many printing techniques it is advantageous for the dielectric to be processed as a liquid (e.g. in the form of a prepolymer or a solution, suspension or slurry) that can be solidified after patterning. Many types of thermally or photochemically curable polymers are well-suited for the dielectric layer. Polyimide and poly(methyl methacrylate) are examples of such materials. Other examples of suitable dielectric materials include photodefinable polymer dielectrics and spin-on glass.

[0030] After the conducting and dielectric layers are formed on the substrate, either the source electrode 225 and drain electrode 226 of the FET 201 or (referring to the alternate embodiment in FIG. 3) the semiconducting material 230 of the FET are deposited. FIG. 2 illustrates the embodiment of the present invention wherein the semiconducting material layer of the FET device is formed after the source and drain electrodes of the FET are formed. FIG. 3 illustrates the embodiment of the present invention wherein the semiconducting material layer of the FET device is formed before the source and drain electrodes of the FET are formed. The configuration depicted in FIG. 2 is advantageous because the contacts are easier to pattern and the contact deposition does not affect the semiconductor layer, which is deposited after contact formation. However, the configuration in FIG. 3 is advantageous because the top contact provides a better interface for electrical interconnection and the interface between the semiconductor and top contacts is more easily modified (if required) for improved electrical interconnection.

[0031] In the embodiments of the present invention wherein the electrodes are printed onto the substrate, it is advantageous to deposit the semiconducting material first because printed electrodes are often relatively thick and not amenable for use in FETs that employ active material deposited over the electrodes. Materials for the electrodes should be good conductors, chemically compatible with the dielectric (e.g. they should be exist in solvents that do not disturb the dielectric material), and suitable for use with printing methods (e.g. for some printing techniques, they should be solvent processable). The properties of the interface between the electrode and the active material should also allow for acceptable operation of the FET. In some embodiments, the properties of the interface are improved by forming interlayers with certain desirable properties between the electrode and the active material. Examples of electrode materials that satisfy these criteria include conducting carbon deposited from suspension, polyaniline deposited from solution, conducting silver paste, and the materials previously described.

[0032] Referring to FIG. 2, once the electrodes 225 and 226 are formed, the semiconductor material 230 is deposited. This material should have properties that yield FETs with the required performance. For most applications, mobilities greater than 10^{-3} cm^2/Vs and on/off ratios greater than 10 (and a conductivity less than 10^{-5} S/cm) are sufficient. Although the semiconductor layer 230 only needs to be present in the narrow region between the source 225 and drain 226 electrodes, it is advantageous to choose a semiconductor material that can also serve as a hole transporter 235 for the LED 202.

[0033] Examples of such materials include the following p-type semiconducting materials: oligothiophene (i.e. Di-R-α-nT wherein n is 4 to 8, T is 2,5-thiophenediyl and R is either C_mH_{2m+1} wherein m is 0 to 18 or $C_yH_{2y+1}OC_zH_{2z}$ where z+y = 4 to 17, y is greater than zero, and z is greater than 2); pentacene; Di-R-anthradithiophene (wherein R is as previously described); bisbenzodithiophene; and phthalocyanine coordination compounds wherein the coordinate is either a metal such as copper, zinc, tin, or iron, or hydrogen. Suitable anthradithiophene semiconductors are described in Laquindanum, J, et al., "Synthesis, Morphology, and Field-Effect Mobility of Anthradithiophenes," <u>J. Am. Chem. Soc.</u>, Vol. 120, pp. 664-672 (1998), which is incorporated by reference herein. Suitable benzodithiophenes are described in Laquindanum, et al., "Benzodithiophene Rings as Semiconductor Building Blocks," <u>Adv. Mater.</u> Vol. 9 (1), pp. 36-39 (1997), which is hereby incorporated by reference.

[0034] Such materials are deposited using vacuum deposition. Some of the above-described materials such as Di-R-α-nT wherein n is 4 to 8 and R is C_mH_{2m+1} wherein m is 4 to 6 and Di-R-anthradithiophene (wherein R is C_6H_{13}) have finite solubility in certain solvents including aromatic solvents such as chlorobenzene and 1,2,4-trichlorobenzene. Therefore these materials can be deposited on a substrate by spin-coating, casting, and printing. FETs with these semiconductor materials, and the fabrication of such devices, are described in Katz, H., et al., "Synthesis, Solubility, and Field-Effect Mobility of Elongated and Oxa-Substituted α,α-Dialkyl Thiophene Oligomers. Extension of 'Polar Intermediate' Synthetic Strategy and Solution Deposition on Transistor Substrates," <u>Chem. Mater.</u>, Vol. 10, No. 2, pp. 633-638 (1998), which is hereby incorporated by reference. These compounds can be cast into a film with a lower off conductivity than other liquid phase, high mobility films, thereby providing a film with a higher on/off ratio.

[0035] As illustrated in FIG. 2, the semiconducting material in this embodiment is deposited uniformly over both the FET 201 region and the LED 202 region, and patterning is not required. If the semiconducting material 230 needs to be patterned (FIG. 3), it is preferred that the material is printable, and that the material is soluble in a solvent that is compatible with the dielectric and electrode materials. Poly(3-alkylthiophene) wherein the alkyl group contains about 2 to about 10 carbon atoms is a material that satisfies these requirements. Such TFT devices are described in Bao, Z., et al., "Soluble and processable regioregular poly(3-hexylthiophene) for

drain and source electrodes are formed thereon.

[0047] In yet another embodiment, a single LED active layer is formed by either printing, casting, or spin coating a solution containing poly(2-methoxy-5-2'-ethyl-hexoxy)-1,4-phenylene vinylene Examples of other active materials that can be deposited in a like manner, and conditions suitable for such deposition are described in Kraft, A., et al. "Electroluminescent Conjugated Polymers-Seeing Polymers in a New Light," Angew. Chem. Int. Ed., Vol. 37, pp. 402-428 (1998), which is hereby incorporated by reference.

[0048] In certain embodiments of the present invention, more than one TFT is monolithically integrated with one or more LEDs. In certain instances, when more than one TFT is integrated with a single LED, the power dissipation at the LED is greatly reduced. When the device of the present invention is incorporated into displays and/or systems, it is contemplated that one or more TFTs will drive one or more LEDs. Displays will have multiple rows and multiple columns of the monolithically integrated device of the present invention. Systems with the device of the present invention will also include appropriate drive circuitry.

Claims

1. A device comprising a light emitting diode monolithically integrated with at least one thin film transistor wherein the light emitting diode comprises an anode, a cathode and at least one active layer comprising a light-emitting material sandwiched between the anode and the cathode and the thin film transistor comprises a semiconductor material interposed between source and drain contacts such that a current that flows from the source to the drain flows through the semiconductor material from the source to the drain, wherein the thin film transistor and the light emitting diode are formed on a single, unitary substrate, and wherein the semiconductor material of the thin film transistor and at least one active layer of the light emitting diode is an organic material.

2. The device of claim 1 wherein the thin film transistor further comprises a gate formed on the substrate and wherein the anode of the light emitting diode and the gate of the thin film transistor are a single layer of material.

3. The device of claim 2 wherein the active layer further comprises a layer of a charge carrying material.

4. The device of claim 3 wherein the semiconductor material of the thin film transistor and the charge carrying material of the light emitting diode are the same material.

5. The device of claim 4 wherein the charge carrying material is a hole transporter material.

6. The device of claim 5 wherein the charge carrying material and the semiconductor material are selected from the group consisting of oligothiophene, pentacene, Di-R-anthradithiophene wherein R is either C_mH_{2m+1} wherein m is 0 to 18 or $C_yH_{2y+1}OC_zH_{2z}$ where z+y = 4 to 17, y is greater than zero, and z is greater than 2, bis-benzodithiophene, phthalocyanine coordination compounds, and regioregular poly(3-alkylthiophene).

7. The device of claim 4 wherein at least one of the source and drain contacts is electrically connected to the anode.

8. The device of claim 7 wherein the substrate is a transparent substrate and the gate of the thin film transistor and the anode of the light emitting diode are indium tin oxide.

9. The device of claim 8 wherein the transparent substrate material is selected from the group consisting of glass, polyester, and polyimide.

10. The device of claim 9 wherein a plurality of thin film transistors is monolithically integrated with the light emitting diode.

11. A process for fabricating a monolithically integrated thin film transistor and a light emitting diode comprising:

    forming a gate contact of a thin film transistor and an anode of a light emitting diode on a unitary substrate
    forming a layer of dielectric material over the gate contact;
    forming a layer of an organic semiconductor material over the layer of dielectric material;
    forming a source contact and a drain contact of the thin film transistor, wherein the source contact and the drain contact are formed either before or after the layer of organic semiconductor material is formed over the layer of dielectric material and wherein one of the source contact and the drain contact are electrically interconnected to the anode;
    forming a layer of an organic light-emitting material over the anode of the light-emitting diode; and
    forming a cathode over the organic light-emitting material.

12. The process of claim 11 wherein the gate contact and the anode are formed from a single layer of conductive material.

FIG. 1
(PRIOR ART)

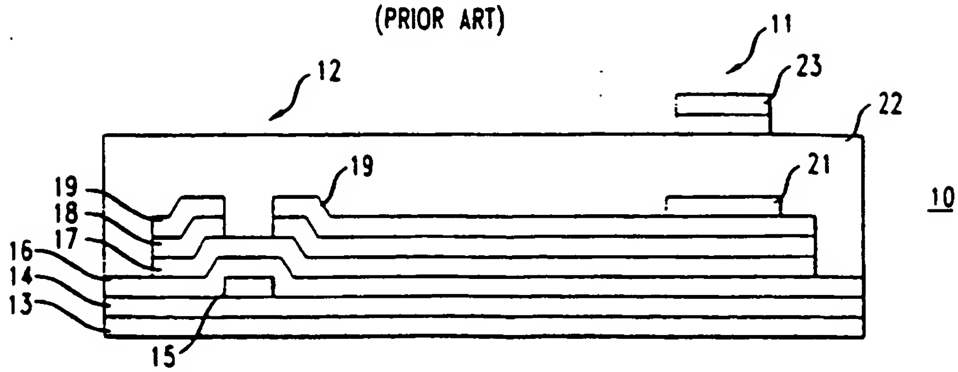


FIG. 2

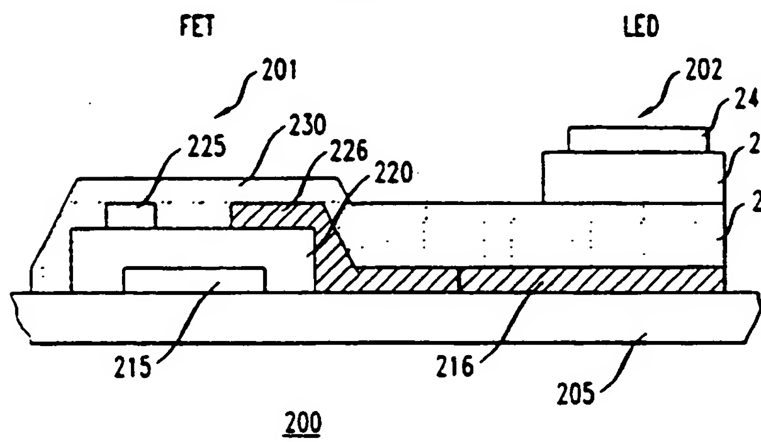
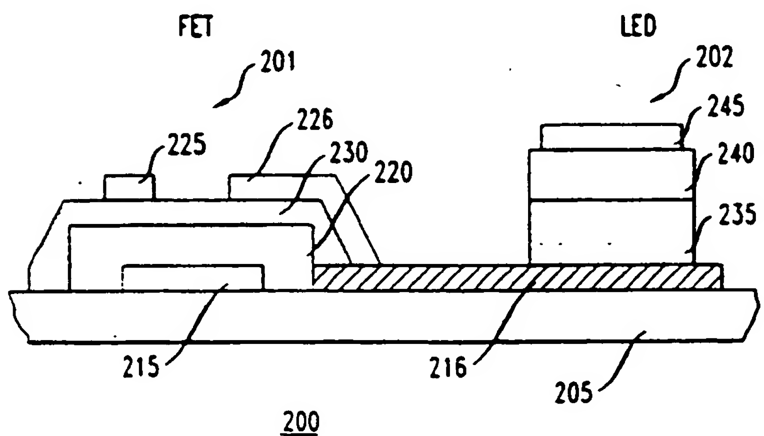


FIG. 3



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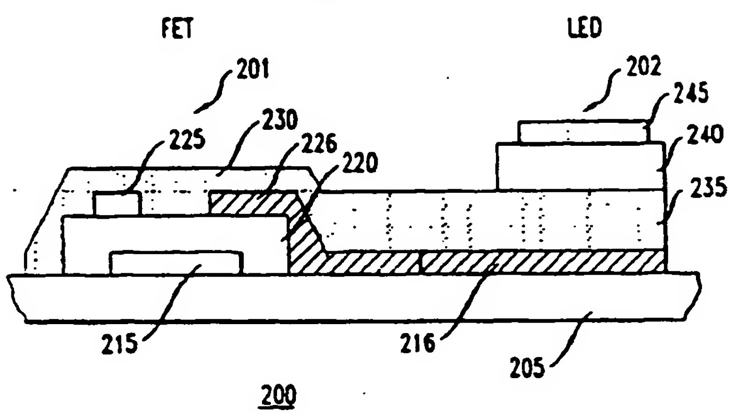

EP 0 962 984 A3

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Patent document cited in search report	Publication date	Patent family member(s)	Publication date
WO 9954936 A	28-10-1999	NONE	

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